Radiative Transfer Modeling of Passive Circumstellar Disks: Application to HR 4796A

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Abstract. We present a radiative transfer model which computes the spectral energy distribution of a passive, irradiated circumstellar disk, assuming the grains are in radiative equilibrium. Dependence on the radial density profile, grain temperature estimation, and optical depth profiles on the output SED are discussed. The best fit model for HR 4796A has a minimum and maximum spherical grain size of 2.2 and 1000 μm respectively, a size distribution slightly steeper than the "classical" -3.5 MRN power law, grains composed of silicates, trolite, ice, and organics and a peak radial density of 1.0×10^{-17} g cm^{-3} at 70 AU, yielding a disk mass of roughly $2M_{\oplus}$.

1. Introduction

Modeling of the spectral energy distribution (SED's) of circumstellar disks can potentially yield a wealth of information about the system under investigation. Sophisticated disk models have recently been developed by Chiang and Goldreich (1997) and Wolf (1999) for T Tauri disks, and basic modeling of older, optically-thin Vega-like disks was performed by Artymowicz (1989) for β Pictoris and Augereau et al. (1999) (hereafter, AG 99) for HR 4796A.

We present a radiative transfer model of passive, Vega-like dusty disks that more rigorously treats the optical properties of disk grains and emergent intensity from along the observer's line of sight than AG 99, allowing for better constraints of grain composition, surface density profiles, and disk mass. HR 4796A was chosen as a test system because of the large number of infrared

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excess flux measurements in the near infrared to submillimeter regions of the spectrum (summarized in Table 1) and restrictions on disk geometry, providing tighter constraints for disk model input parameters.

Table 1.   Infrared and submillimeter flux measurements for HR 4796A used to constrain the model.

λ	Excess Flux (Jy)	Uncertainty (Jy)	Source
11.6	0.086	0.070	Fajardo-A. et al. (1998)
12.5	0.101	0.018	Koerner et al. (1998)
12.5	0.133	0.027	Fajardo-A. et al. (1998)
18.2	1.100	0.150	Jayawardhana et al. (1998)
20.0	1.860	unknown	Jura et al. (1993)
20.8	1.813	0.170	Koerner et al. (1998)
24.5	2.237	0.700	Koerner et al. (1998)
25.0	3.250	0.130	IRAS
60.0	8.630	0.430	IRAS
100.0	4.300	0.340	IRAS
450.0	0.180	0.150	Greaves et al. (2000)
800.0	< 0.028		Jura et al. (1995)
850.0	0.0191	0.0034	Greaves et al. (2000)

2.   Passive Circumstellar Disk Modeling Theory

The emergent flux from a passive, optically thin circumstellar disk at some wavelength equals the wavelength dependent intensity of light emerging from a point in the disk integrated over the solid angle that the disk comprises:

$$F_\nu = D^{-2} \int_0^{2\pi} \int_0^r I_\nu r_m sin(i) dr_m d\omega \tag{1}$$

where D is the star's distance from the Earth, I_ν is the emergent intensity at a point in the disk with midplane radius r_m, and i is the inclination angle where $i = 90$ corresponds to a face-on disk. The intensity emergent from each point in the disk is calculated by solving the radiative transfer equation and integrating the intensity contribution from all grains along the line of sight:

$$I_\nu(r) = \int_0^s B_\nu(T)\kappa(\lambda)\rho(r)ds \tag{2}$$

where κ is opacity, and ρ is mass density of grains. The grains' effective temperatures, T_g, are computed assuming dust grains are in radiative equilibrium:

$$q_{uv}(R_*/r)^2 \sigma T_*^4 = 4 \int_0^\infty q_{ir} B_\nu(T_g) d\nu \tag{3}$$

where q_{uv} (early A stars like HR 4796A emit mostly UV photons) and q_{ir} are respectively the absorption efficiencies for incident and emitted radiation. Because grain extinction coefficients are wavelength dependent, and, in more rigorous
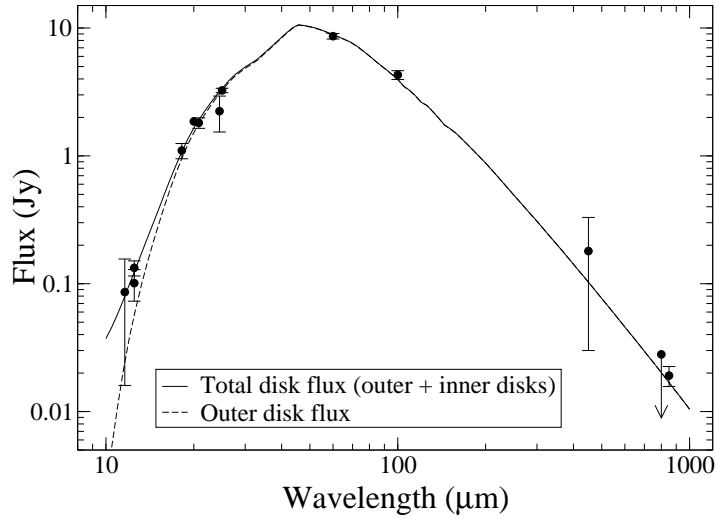
Figure 1.   Full synthetic SED for outer disk and total disk contribution compared against observed infrared excess measurements.

treatments, cannot be expressed as a simple analytic function, one must numerically solve for the grain temperature. Grain temperatures are calculated over a grid of grain sizes and distances. Resolved images of the HR 4796A disk infer a radial density profile sharply peaked at 70 AU of the form $\rho(r) = \rho_o(r/rc)^\gamma$ where $rc = 70$AU, γ is γ_{in} for $r \leq rc$ and γ_{out} for $r > rc$ are the inner and outer radial density power law factors, ρ_o is the peak radial density, and rm is the distance at which this occurs. Wavelength-dependent opacities are calculated from the Semenov et al. (2002) compositional model for chemically homogeneous, spherical grains whose primary components are pyroxene, olivine, volatile and refractory organics, water ice, trolite, and iron: similar to the Pollack (1994) compositional model. The optical properties of dust particles are computed via Mie theory. The grain size distribution is initially set to the size distribution for interstellar grains as prescribed by Mathis (1977). Minimum size is set at 5 μm for HR 4796A: close to the blowout size limit as inferred by AG 99. These two parameters are then adjusted to yield an optimum SED fit.

3.   Modeling Results

Results of the disk modeling effort are shown in Figure 1. Optimum fit of the SED was achieved with the following input parameters: $a_{min} = 2.2$ μm, $\beta = -3.86$, $\gamma_{in} = 10$, $\gamma_{out} = -12$, and $\rho_o = 1.0 \times 10^{-17}$ g cm^{-3}. An additional hot dust component peaked at 9 AU was required to fit the SED. Predicted flux values fall within the margin for error of measured values at nearly all wavelength points. The best fit requires a minimum size smaller than the blowout size limit for the system. Thus, some of the dust grains are not primordial and may be replenished via collisions of larger bodies. This model gives a disk mass of roughly $2.05 M_\oplus$: consistent with dynamical calculations of the disk mass (AG 99) and Greaves (2000) calculation of $M_{disk} \geq 0.25 M_\oplus$ and does so without

using scaling factors or 'fitting parameters'. The only true free parameter is the peak radial density. The radial density power laws can be qualitatively inferred from resolved images of the disk. The emergent SED varies so wildly with the grain composition assumptions that only a very small subset of possible compositions (which turn out to be quite similar) will yield empirically accurate model predictions. Finally, the gas/dust ratio, while not known, can be crudely constrained, and from this type of modeling one can produce a grid of models having a range of peak densities and gas/dust ratios. From Greaves (1999), the gas mass must be $< 7M\oplus$ and the age and optical depth of the HR 4796A disk suggest a small gas/dust ratio: this is consistent with our results.

4.   Future Tasks

The main remaining task is to make the absorption/extinction coefficient treatment self-consistent. While the grain optical properties of the were treated rigorously in the opacity calculations, grain temperatures themselves were calculated using a crude analytical function characterizing the extinction coefficients for the grains. While the derived grain temperatures concur roughly with previous temperatures derived by AG 99, a self-consistent approach would ensure more accurate grain temperatures. Second, a mechanism for confining HR 4796A's disk material into its narrow, sharply peaked annulus should be sought. Wyatt et al. (1999) suggested that orbital resonances with a jovian mass planet interior to the main disk could be responsible: reminiscent of the Goldreich and Tremaine (1982) discussion of ring confinement by shepherding moons. Finally, similar models could be produced for Vega, a slightly older, early A-type star which seems to be tracking an evolutionary path similar to that of HR 4796A, with results compared to previous modeling attempts for this system.

References

Artymowicz, P., Burrows, C., & Paresce, F. 1989, ApJ, 337, 494

Augereau, J. C., Lagrange, A. M., et al. 1999, A&A, 348, 557

Chiang, E., & Goldreich, P. 1997, ApJ, 490, 368

Fajardo-Acosta, S. B., Telesco, C. M., & Knacke, R. F. 1998, AJ, 115, 2101

Goldreich, P., & Tremaine, S. 1982, ARA&A, 20, 249

Greaves, J. S., Mannings, V., & Holland, W. 2000, Icarus, 143, 147

Jayawardhana, R., Fisher, S., Hartmann, L., et al. 1998, ApJ, 503, L79

Jura, M., Zuckerman, B., et al. 1993, ApJ, 418, L37

Jura, M., Ghez, A. M., et al. 1995, ApJ, 445, 451

Koerner, D. W., Ressler, M. E., et al. 1998, ApJ, 503, L83

Pollack, J. B., Hollenbach, D., et al. 1994, ApJ, 421, 615

Semenov, D., Henning, Th., & Ilgner, M. 2002, A&A, in preparation

Wolf, S., Henning, Th., & Stecklum, B., 1999, A&A, 349, 839

Wyatt, M., & Dermott, S. F. 1999, ApJ, 527, 918